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Dynamics of the periphery current in Rhode Island Sound

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ABSTRACT

Observations reveal a near-surface circulation around the periphery of Rhode Island Sound (RIS) that occurs in summer stratified conditions and disappears in winter when weak solar insolation and wind stirring result in strong vertical mixing. According to a series of numerical simulations and theoretical analysis, we attribute the summer intensification of this "periphery current" to a circulation produced by seasonal bottom thermal fronts often observed from May to September. The strength of the thermal fronts is proportional to the surface solar radiation. Meanwhile, the simulations capture a continuous topographically rectified tidal residual current in RIS and a pair of opposite-sign headland eddies around Montauk Point in Block Island Sound (BIS). Our analysis suggests the importance of nonlinear vorticity advection and frictional torques in BIS. On the other hand, the vorticity balance shows the importance of velocity torque by contributing to the opposite headland gyres, while the effect by planetary vorticity stretching is negligible over BIS but important in RIS.

1. Introduction

Rhode Island Sound (RIS), a semicircular embayment off the southern Rhode Island and Massachusetts coast, is located offshore of the mouth of Narragansett Bay and bounded to the west by Point Judith and Block Island (BI) and to the east by Martha's Vineyard and the Elizabeth Islands (Fig. 1). Waters in RIS are connected with Block Island Sound (BIS) through the gap between Point Judith and BI. Based on field measurement, Codiga and Ullman (2010) identified a cyclonic, near-surface circulation around the periphery of RIS that is usually present in summer, stratified conditions and then disappears in winter when weak solar insolation and wind stirring results in strong vertical mixing. In summer, the circulation is characterized by residual current moving along the coast of Rhode Island, flowing north into RIS from the southeast, to the west at the inner shelf (Kincaid et al., 2003) where it encounters potentially significant dynamical exchange processes associated with Narragansett Bay, and then to the southwest in the western portion of RIS and south of Block Island (Ullman and Codiga, 2004). A seasonal thermocline accompanies this circulation in spring and summer (Shonting and Cook, 1970). During the winter months this entire flow pattern collapses, with much weaker currents and different trajectories (Codiga and Ullman, 2010).

Tidal residual effect is a significant dynamical contributor to the circulation in RIS (Luo et al., 2013), but the dynamics that gives rise to the strong tide-generated gyre around RIS is still an open issue. Pingree (1978) and Zimmerman (1981) introduced a novel approach to understanding the mechanisms of tidal residual circulations by examining the vorticity of tidal flows, and Robinson (1981) provided further insights based on the transfer of tidal vorticity to the mean field. Moreover, Robinson (1981) illustrated the unique role of quadratic bottom friction when there was a topographic slope perpendicular to the tidal residual currents. To fully understand the sources of tidal residual circulations, Ridderinkhof (1989) used the depth-averaged vorticity equation to show that the essential balance was provided by the advection and dissipation of tidal vorticity generated by column stretching and squeezing, and by the frictional torque due to depth gradients and velocity shear. One purpose of this study is to detail the dynamics of the tidal residual circulation in and around RIS.

In addition to the tidal residual current, another competing hypothesis for the circulation in RIS involves a thermohaline circulation. The circulation is in thermal wind balance with the sharp horizontal, temperature and salinity fronts, which are usu-

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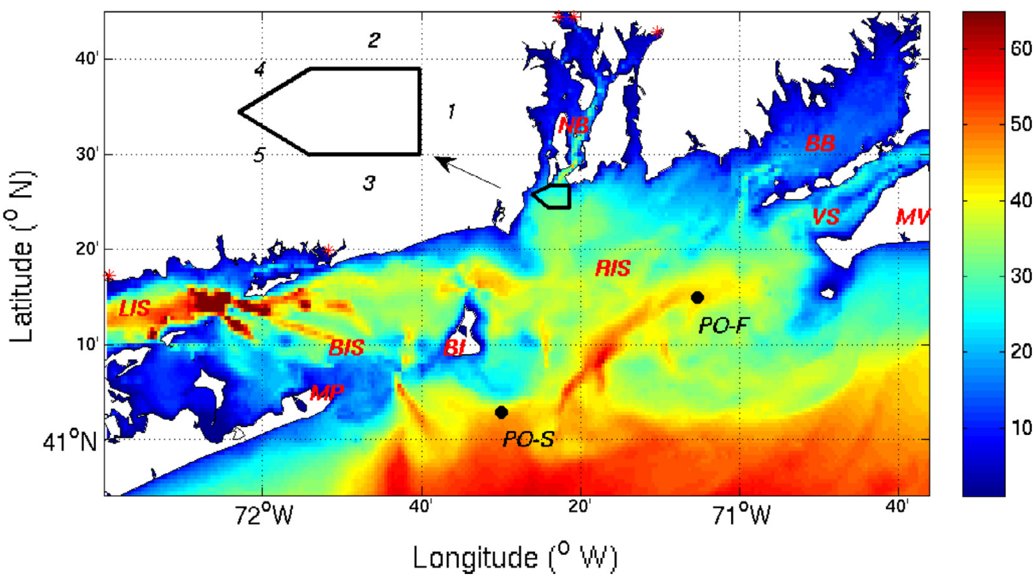

Fig. 1. Bathymetry around RIS and BIS. Place names: Long Island Sound (LIS), Montauk Point (MP), Block Island Sound (BIS), Block Island (BI), Rhode Island Sound (RIS), Narragansett Bay (NB), Buzzards Bay (BB), Vineyard Sound (VS), Martha's Vineyard (MV). The cruise lines at the mouth of Narragansett Bay are represented by black lines: (1) Brenton Reef, (2) East Passage, (3) South Line, (4) West Passage, (5) Narragansett Beach. The red stars are the outfalls of, from left to right, the Connecticut River, Pawcatuck River, Pawtuxet River, Blackstone River and Taunton River.

ally present in spring and summer. The horizontal fronts are produced by the spatially varying distribution of tidal mixing (Hill et al., 2008), which has been found in many other shallow tidal areas in the Northern Hemisphere (Horsburgh, 2000). Codiga and Ullman (2010) suggested the possibility that the summer intensification of the RIS periphery flow was tied to sharpened horizontal density gradients associated with tidal mixing fronts.

In addition to the periphery current, a pair of eddies around Montauk Point was present in the numerical simulations of both Edwards (2004) and Luo et al. (2013). Similar closely-connected headland eddy pairs have been found in other regions and their dynamics have been attributed to many different mechanisms, with bottom frictional torque (Pingree, 1978; Geyer and Signell, 1990) and no-slip lateral 'wall' boundary friction proposed by Zimmerman (1981) being the most popular. In the mechanism by Zimmerman (1981), the velocity gradient normal to the wall is associated with the wall's lateral frictional boundary layer that is then transported to the mean field from the oscillating tidal field by the nonlinear advection of vorticity. Based on the analysis of the transport vorticity equation around an idealized, symmetric promontory in a numerical simulation, Park and Wang (2000) attributed the eddies to the transfer of topographic vorticity, which is consistent with the interpretation by Robinson (1981). In essence, the side-wall boundary works the same way in generating the velocity gradients as a slope that gradually shoals around a promontory (Zimmerman, 1981). In BIS, the topographic features make the situation rather more complicated. Edwards (2004) has emphasized the importance of vortex stretching and tilting for the anticyclonic eddy south of Montauk Point without, however, connecting it with the cyclonic eddy to the north of Montauk Point.

The purpose of this study is to examine the sources of the topographically rectified residual currents in RIS and BIS, and to investigate the role of both tidal residual currents and deep thermohaline gradients in the summer circulation in RIS through both a series of three-dimensional numerical simulations and theoretical analysis. The numerical model configuration, design and model validation are described in Sections 2 and 3. The tides over RIS and BIS are depicted in Section 4, and the contributions from bottom thermal gradients are presented in Section 5. In Section 6, we discuss the tidal rectification process, and a criterion is used to quantitatively

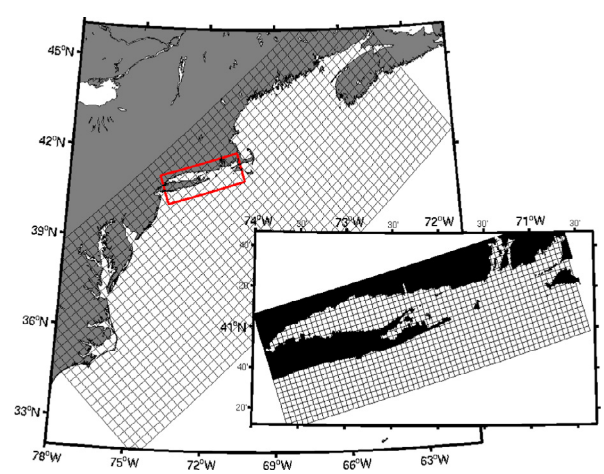

Fig. 2. Model configurations. The local-scale ROMS grid (plot every 6 grid points) has an uniform horizontal resolution of 800 m, and the regional-scale ROMS grid (plot every 6 grid points) is uniform with a resolution of 5 Km.

describe the contributions from steric height and non-steric height. A summary is given in Section 7.

2. Methods

The numerical simulations are performed using the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 1998; 2003; 2005; Haidvogel et al., 2000) that employs a terrain-following coordinate for the vertical. The high resolution 'local' domain covers RIS, BIS, Long Island Sound (LIS) and the adjacent inner shelf area, with a uniform horizontal grid of 800 m and 30 terrain-following vertical layers, and this domain is one-way nested within a 'regional' domain with a constant horizontal resolution of 5 km (Fig. 2). For the regional-scale model, the open boundary conditions are derived from a global eddy resolving model simulation produced by the Hybrid Coordinate Ocean Model (HYCOM)/Navy Coupled Ocean Data Assimilation (NCODA; Chassignet et al., 2003; Cummings, 2005).